Venus atmosphere build-up and evolution : where did the oxygen go? May abiotic oxygen-rich atmospheres exist on extrasolar planets? Rationale for a Venus entry probe

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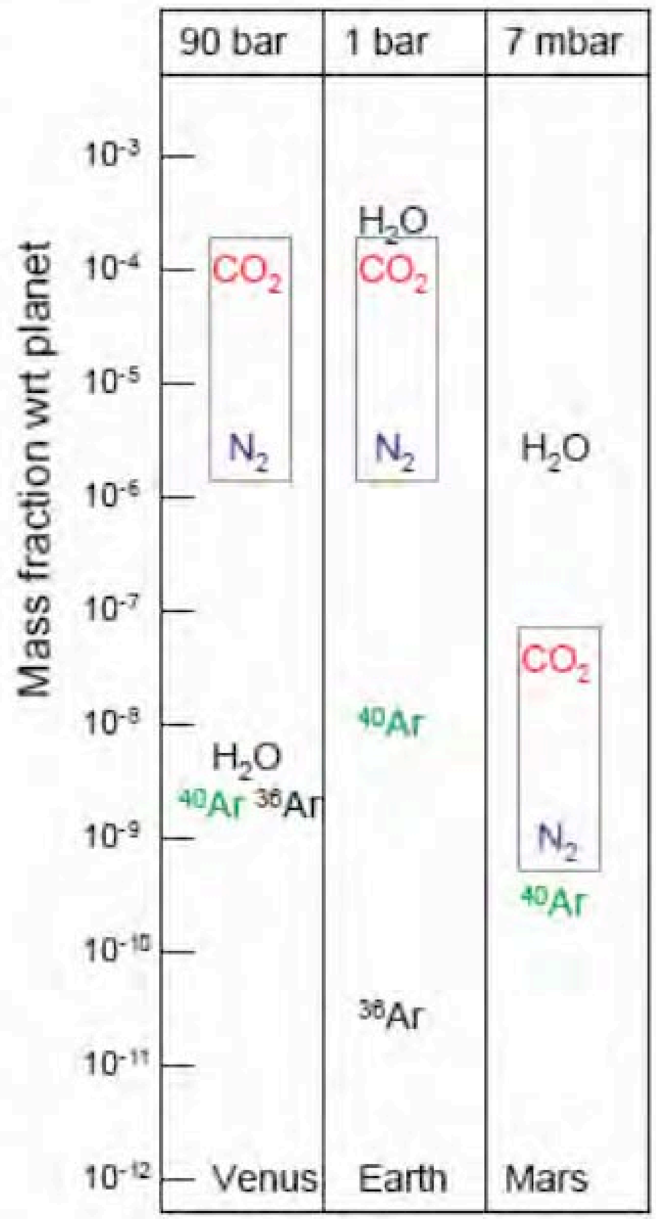
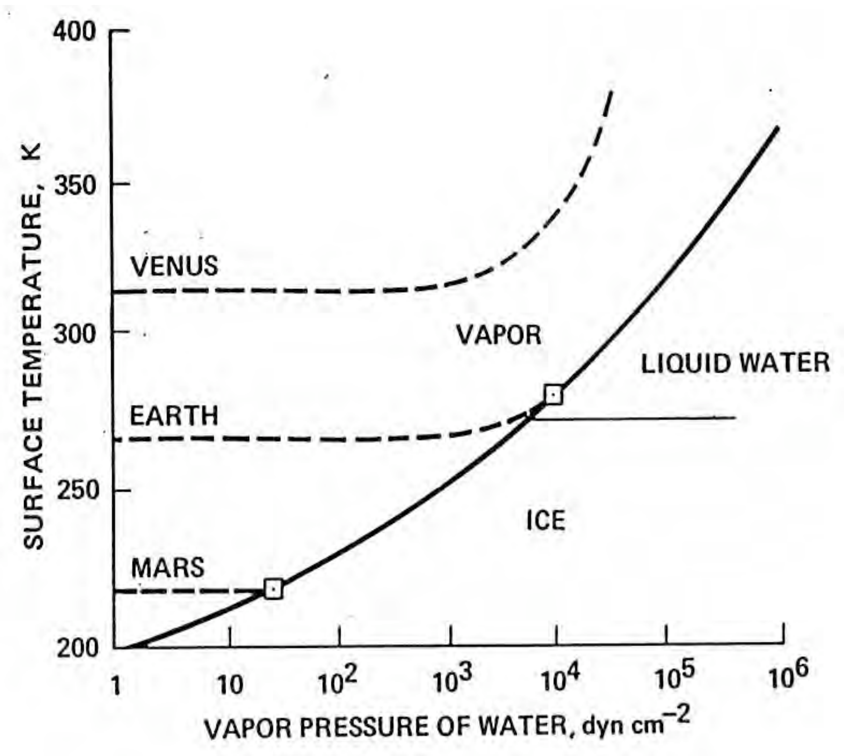
Volatile inventory of terrestrial planets

- Same N_2 and CO_2 inventories on Venus and Earth, much less on Mars (due to escape).
- Three major differences of Venus atmosphere :
  - **I] Virtually no water (a few 10 cm precipitable)**
  - **II] ≈3 times less ^{40}Ar**
  - **III] ≈100 times more ^{36}Ar**



I] Loss of water on Venus



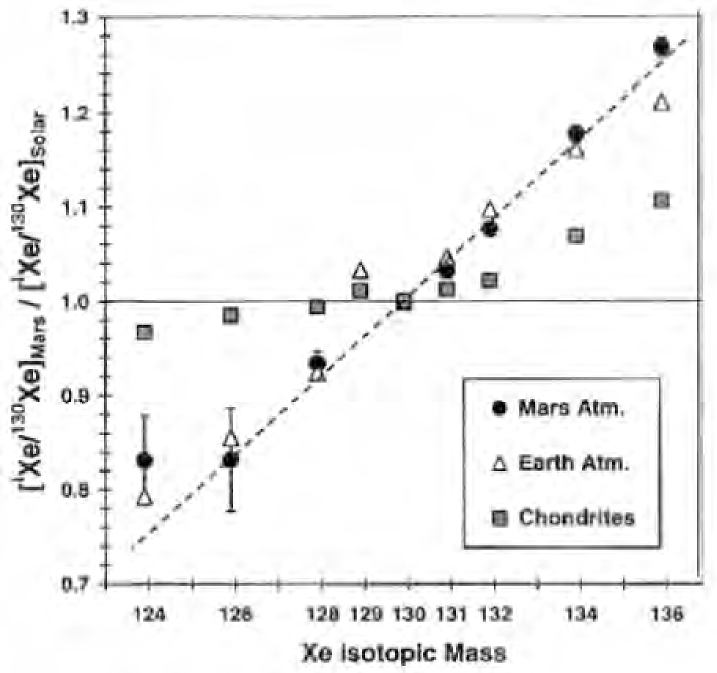
- Runaway (or moist) greenhouse (Rasool and De Bergh, 1970) :
  - Evaporation of the primitive ocean.
  - Photolysis of H_2O in the high atmosphere.
  - Hydrodynamic escape of H.
- Removal of the totality of H contained in 1 TO (Terrestrial Ocean) during the first billion years (Kasting and Pollack, 1983)

Hydrodynamic escape

- Global, cometary-like, expansion of the atmosphere.
- **Requires a large energy deposition rate at the top of the atmosphere** (possible sources : EUV, Solar-Wind -?-, Giant Impact -?-).
- May occur for H or H_2-rich thermospheres in **primitive conditions**, e.g. in the two following cases :
  - Primordial H_2/He atmospheres (all terrestrial planets).
  - Outgassed H_2O-rich atmosphere during an episode on runaway and/or wet greenhouse (Venus case) .
- **Did hydrodynamic escape ever occur on a planet?** Main clues at present time :
  - Isotopic fractionation of Xe on Earth.
  - Loss of the primitive Venus ocean.

Terrestrial xenon

- Terrestrial xenon is heavier than solar and meteoritic Xe.
- May have been produced by GI-driven hydrodynamic escape on primitive Earth (at the time when Moon formed) (Pepin and Porcelli, 2002).
- Mars Xe is similarly fractionated : coincidental (?) if due to hydrodynamic escape.
- **Alternative hypothesis : Xe was already fractionated within pre-planetary carriers.**



What is the isotopic fractionation pattern of Xe on Venus? Crucial question.

Loss of the primitive Venus ocean

- Minimum duration of H escape : > 100 Myr (required for the atmosphere to build up, see e.g. Ahrens et al, 1989).
- **What was the fate of oxygen left behind? Did it escape together with H? Abiotic oxygen atmospheres may in principle form by this process.**
- During hydrodynamic escape of H, an heavy element may be dragged off along with H only if its mass is smaller than a "crossover mass" m_c (see Hunten et al, 1987).
- Assuming EUV-driven escape, and that Φ_{EUV} evolved with time like $(t_0/t)^{5/6}$ (Zahnle and Walker, 1982) :
  - m_c>140 (required for Xe fractionation) at t < ≈40 Myr
  - m_c>16 (required for O removal) at t < ≈600 Myr
- Hydrodynamic escape of O is therefore possible during the first half Gyr.

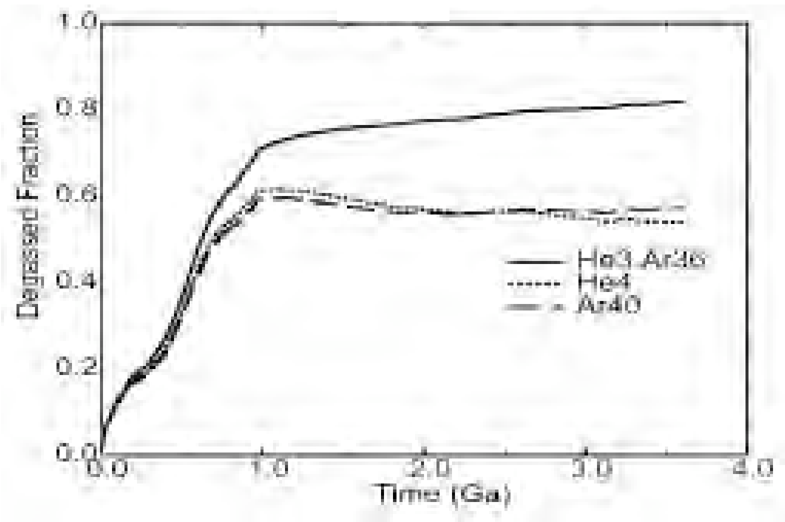
What was the fate of oxygen on Venus?

- **Virtually no oxygen in Venus atmosphere**. Several possible explanations :
- 1) Oxygen was removed by oxidation of surface rocks. Assuming $FeO \rightarrow Fe_2O_3$, **required crust production rate of ≈15 km^3/yr (≈ Earth rate) during 4 Gyr**. Not likely (no plate tectonics like on Earth).
- 2) Oxygen escaped to space :
  - 2a) By impact erosion at the very beginning : possible, but N_2/CO_2 inventories are similar for Venus and Earth!
  - 2b) **By hydrodynamic escape (OK with crossover mass), but it requires another source of energy in addition to solar EUV (Chassefière, 1996).**
- **The primitive, intense, solar wind may have been this additional source (Chassefière, 1997), provided Venus had no Earth-type intrinsic magnetic field.**

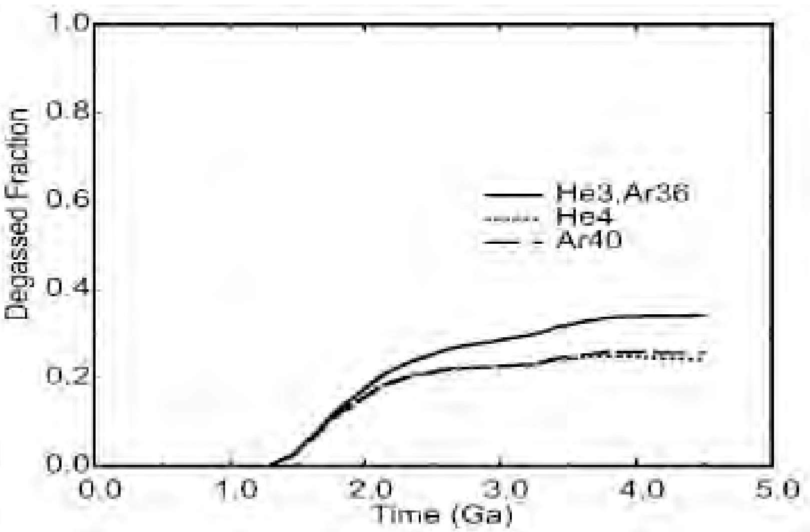
II] About the low Ar 40 Venus inventory

- Low ^{40}Ar level interpreted as the signature of a less outgassed mantle (Xie and Tackley, 2004).

Earth (Ra = 1.3 10^7)



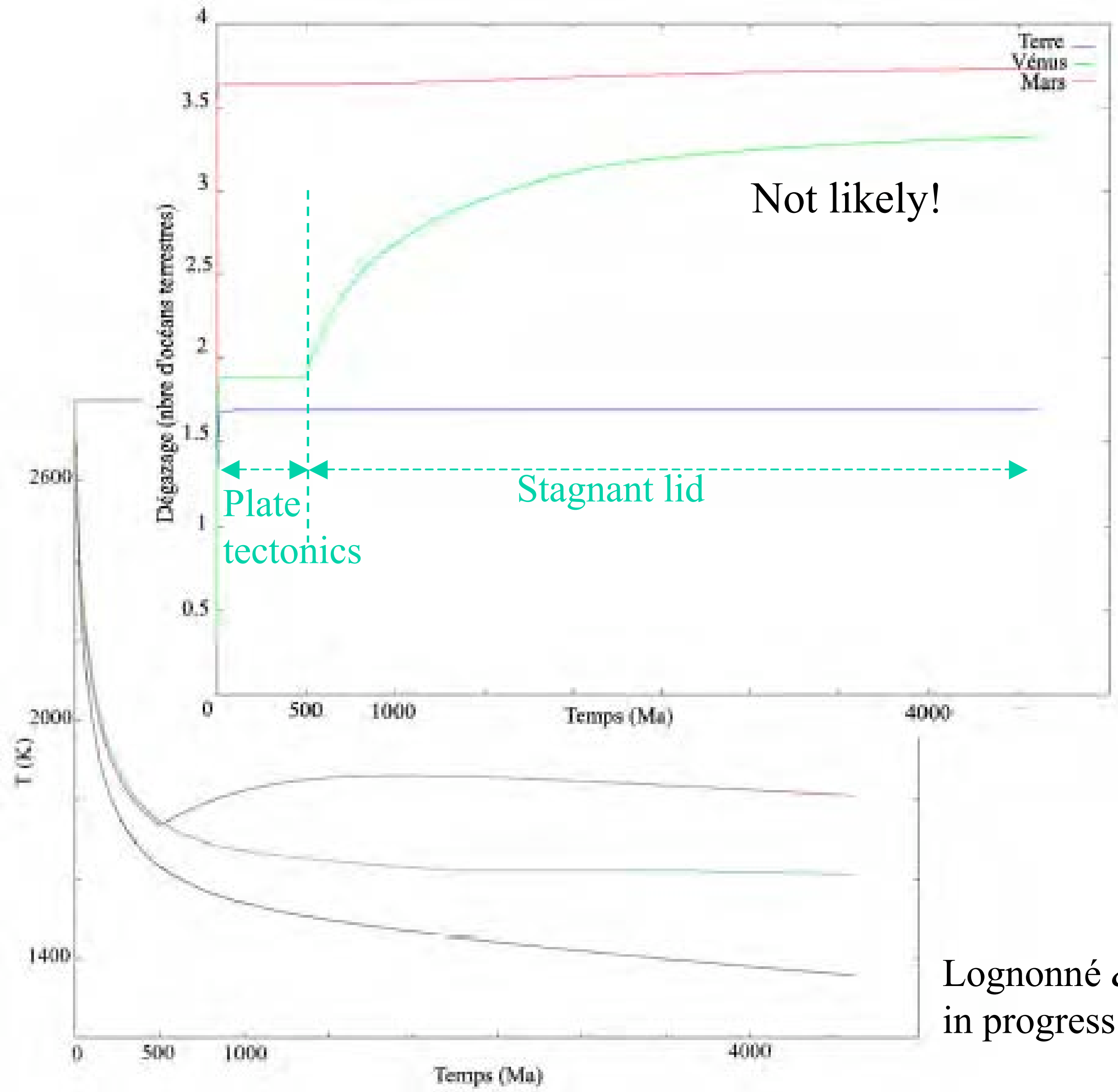
Venus (Ra = 10^6)



Possible link between loss of water and stagnant lid regime

- The present « stagnant lid » regime (different of « plate tectonics » on Earth), making magma transport more difficult, could be due to a more viscous mantle.
- The terrestrial intra-plate crust production rate is similar to the maximum one assumed for Venus.
- **Possible link between the early loss of water (with no rehydration of the mantle, increasing its viscosity) and the stagnant lid regime yielding :**
  - **smaller crust production rate**
  - **lesser outgassing from the interior**

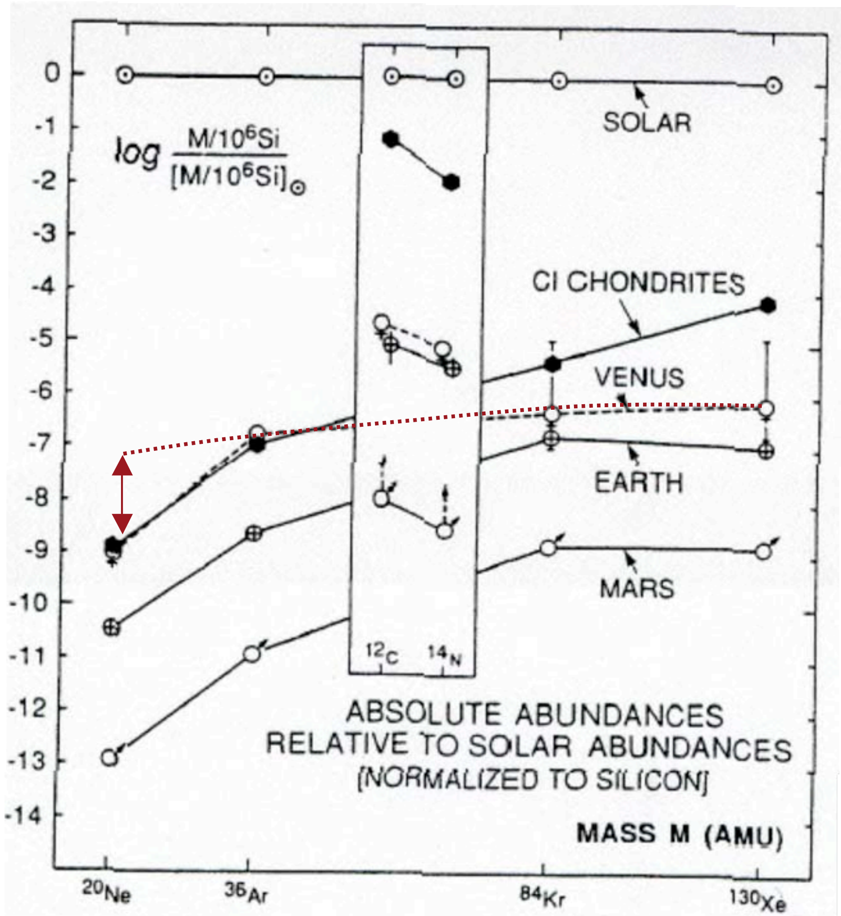
A model coupling mantle and atmosphere



- Mantle convection model taking into account hydration-dehydration.
- Initial content of the mantle : 4 TO.
- At steady state, 1.7 TO in the atmosphere on Earth.
- 1.9 TO in atmosphere on Venus until stagnant lid, slow outgassing later up to 3.3 TO.

Lognonné & Gillmann, work in progress

III] Why so much Ar 36 on Venus…



From Pepin and Porcelli, 2002

- <u>… or so little Kr and Xe?</u>
- Venus noble gas elemental spectrum much more solar like than Earth's and Mars' ones.
- If so, Venus Xe and Kr should not be isotopically fractionated. **What is the fractionation pattern of Kr and Xe on Venus?**
- **Why is Ne depleted with respect to Ar/Kr/Xe?**

Neon and argon isotopes

- $^{20}Ne/^{22}Ne$:
  - 13.7 in solar wind
  - ≈12 on Venus
  - 9.8 on Earth
  - 7-11 in SNC meteorites (Mars).
- **SW > Venus > Earth-Mars : clues to a solar origin**, with some later fractionation by escape.
- $^{36}Ar/^{38}Ar$ similar for the 3 planets (≈5.5) : **suggests no significant fractionation of Ar by hydrodynamic escape.**

Element	Venus value	Earth value
Radiogenic isotopes (mixing ratios)		
^{4}He (ppm)	0.6-12	
^{40}Ar (ppm)	21-51	
^{129}Xe (ppb)	<9.5	
Venus/Earth (abundance ratio)		
^{4}He	175-3700	
^{40}Ar	0.25	
Non-radiogenic isotopes (mixing ratios)		
^{20}Ne (ppm)	4-13	
^{36}Ar (ppm)	21-48	
^{84}Xe (ppb)	7-38	
^{132}Xe (ppb)	<10	
Venus/Earth (abundance ratio)		
^{20}Ne	21 [10-40]	
^{36}Ar	70 [50-110]	
^{84}Kr	3 [1-5]	
^{132}Xe	<35	
Isotopic ratios		
$^{3}He/^{4}He$	$<3\ 10^{-4}$	$1.4\ 10^{-4}$
$^{20}Ne/^{22}Ne$	11.2-12.6	9.8
$^{21}Ne/^{22}Ne$	<0.067	0.029
$^{36}Ar/^{38}Ar$	5.45±0.1	5.32
$^{40}Ar/^{36}Ar$	1.11±0.02	295.5

Large uncertainties

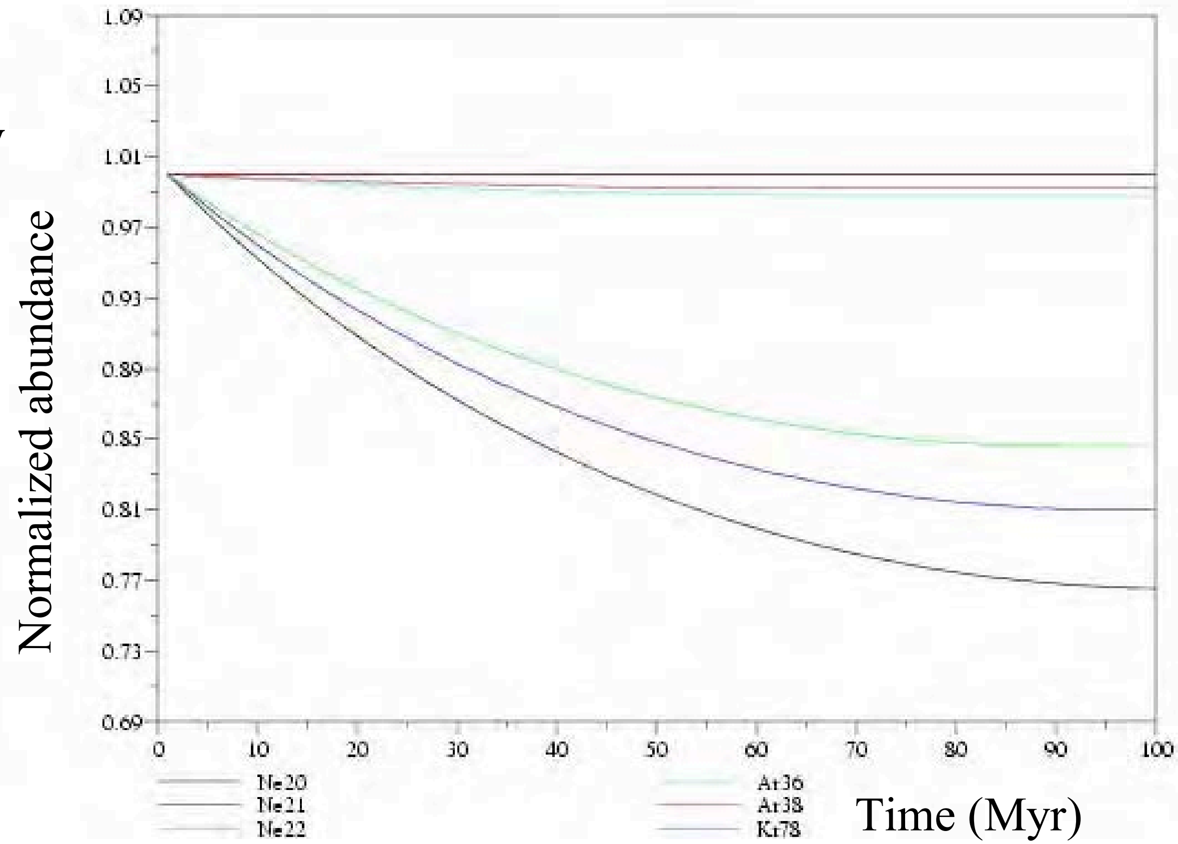
From Wieler, 2002

A model of neon fractionation through hydrodynamic escape

- Hypothesis : Ne fractionation on Venus results from hydrodynamic escape.
- A model has been constructed, by using conditions at the top of Venus atmosphere derived from Kasting and Pollack (1987), and the EUV energy-limited approach :
  – Hydrodynamic flow develops above 200 km altitude, with a bulk velocity at the base of 5 cm s^{-1}.
  – Homopause is located at 120 km, and gravitational fractionation is assumed above.
  – The solar EUV flux decreases as $t^{-5/6}$ (Zanhle and Kasting, 1986).
  – The initial elemental and isotopic ratios of Xe, Kr, Ar and Ne are solar like.

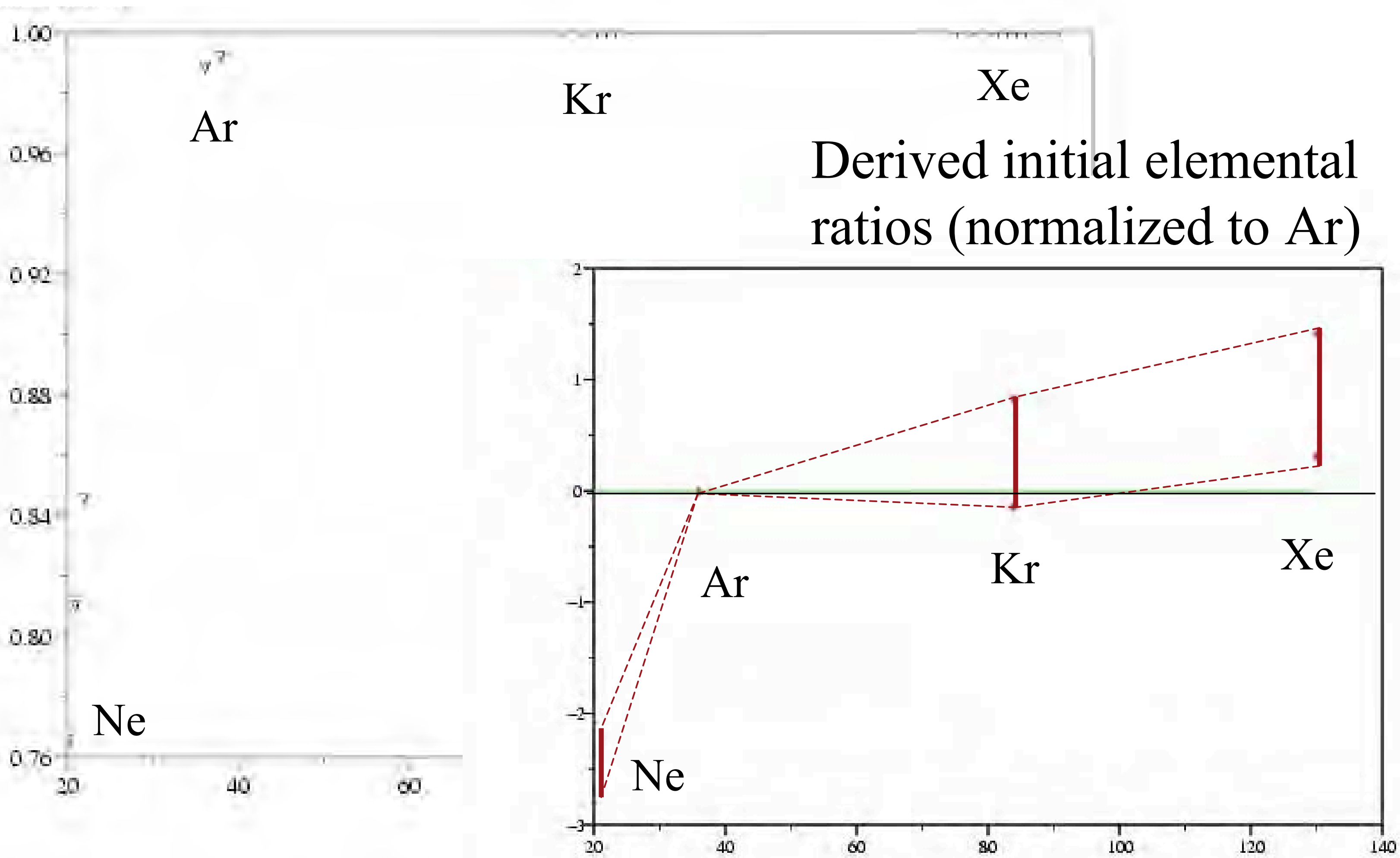
Time evolution of Ar and Ne isotopes

- Kr and Xe are not significantly removed.
- Ar is only slightly removed.
- 20% of Ne is removed, and $^{22}Ne/^{20}Ne$ decreases from 13.7 (solar) to 12.1 (present Venus value)



About ≈2 TO equivalent-H escape

Fractionation pattern and initial elemental pattern



Present state of knowledge and questions

- Small elemental fractionation wrt Sun (except for Ne), suggesting solar origin.
- Observed Ne isotopic pattern put constraints on water loss by hydrodynamic escape.
- Venus atmosphere possibly less evolved than other atmospheres : if so, may be used as a reference for studying other planets.
- Major key : isotopic fractionation pattern of Kr and Xe. Did Venus know an early intense SW-driven hydrodynamic escape phase? Fate of O left behind H?
- Expected relationship between mantle and atmosphere histories.

Expected scientific return from Venus noble gas measurements : atmosphere evolution

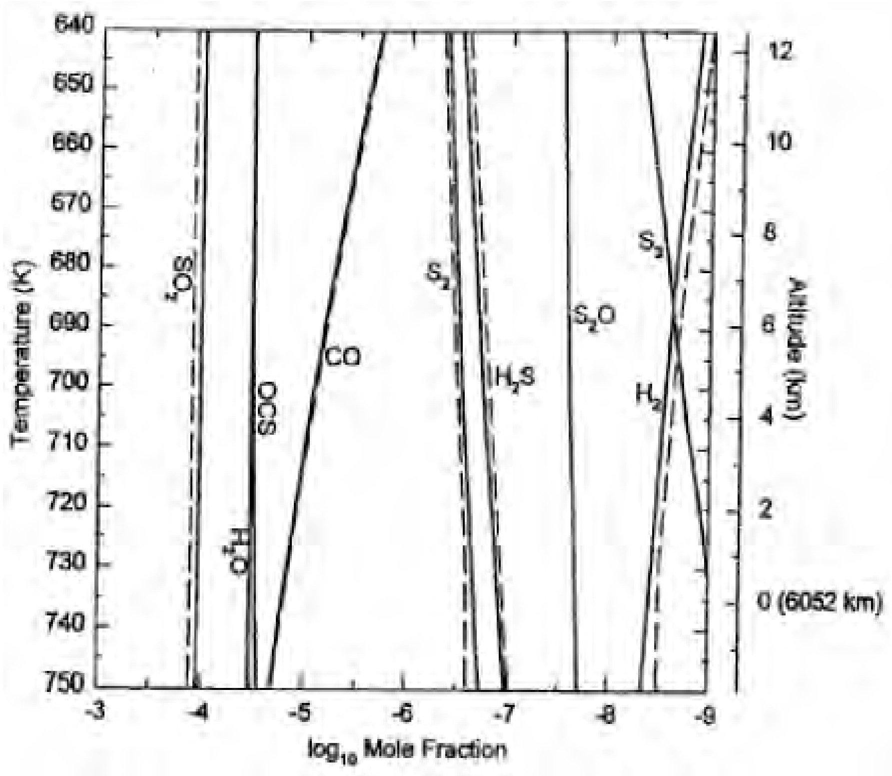
- **Confirm (or not) that Venus noble gas are solar like (not only elemental, but also isotopic ratios).**
- If so,
  - build self-consistent models of water hydrodynamic escape, constrained by isotopic signatures imprinted on noble gases,
  - reassess the current scenarios of Earth and Mars atmosphere evolution by using Venus noble gases as a reference.
- If not so (Venus noble gases are not solar like, e.g. Xe is Earth-like),
  - infer fractionation patterns of noble gases in preplanetary carriers,
  - in intermediate cases (Venus is "between" the Sun and Earth), disentangle effects of pre-planetary and planetary processes.

Implications for mantle convective regime and thermal history

- **Couple mantle convection models and atmospheric models, in terms of water exchange, and of loss of water to space.**
- Model cycling of water to mantle in both "plate tectonics" and "stagnant lid" regimes taking into account EUV and/or SW-powered hydrodynamic escape as a sink of atmospheric water.
- Study the effects of mantle dehydration, if escape is strong, on the transition from "plate tectonics" to "stagnant lid". Construct a self-consistent model of Venus mantle history, time evolution of crust production and outgassing, and atmospheric evolution.

Other measurements of interest

- Vertical profiles of species in the low atmosphere, **including the fugacity of oxygen**.
- Mineralogy of the surface and oxidation state.
- Energetic budget of low atmosphere (radiative, convective, latent and sensible heat fluxes)



From Fegley et al, 1997

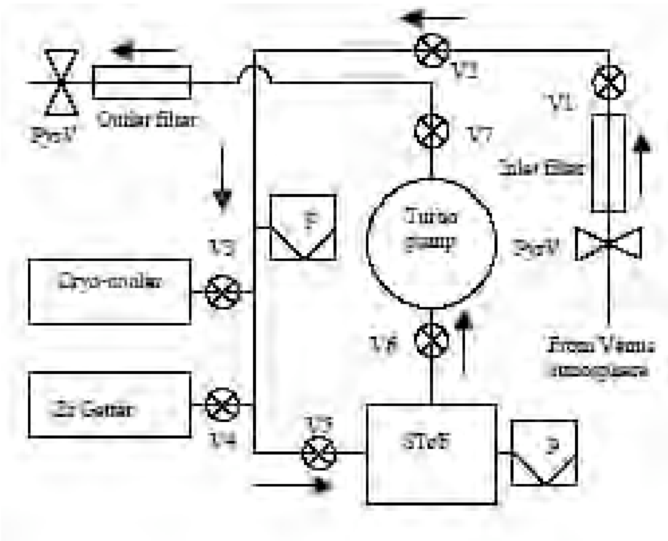
- **Objective: better understand the thermochemical equilibrium between surface rocks and atmosphere.**

A descent probe in Venus atmosphere : a few possible key instruments

- Noble gas mass spectrometer.
- GCMS instrument for chemical composition (gas and clouds), optical gas analyzer.
- Oxygen fugacity sensor
- Nephelometer (clouds)
- Thermal IR spectrometer
- Vis/Near IR spectro-imager
- Atmospheric package (n, T, accelerometer, electrical conductivity)
- Radioelectric, acoustic, magnetic, radioactive tracer sensors.

Additional slides (instruments)

Noble gas mass spectrometer



Possibility of using in parallel, and/or before mass spectrometer, chromatographic columns :

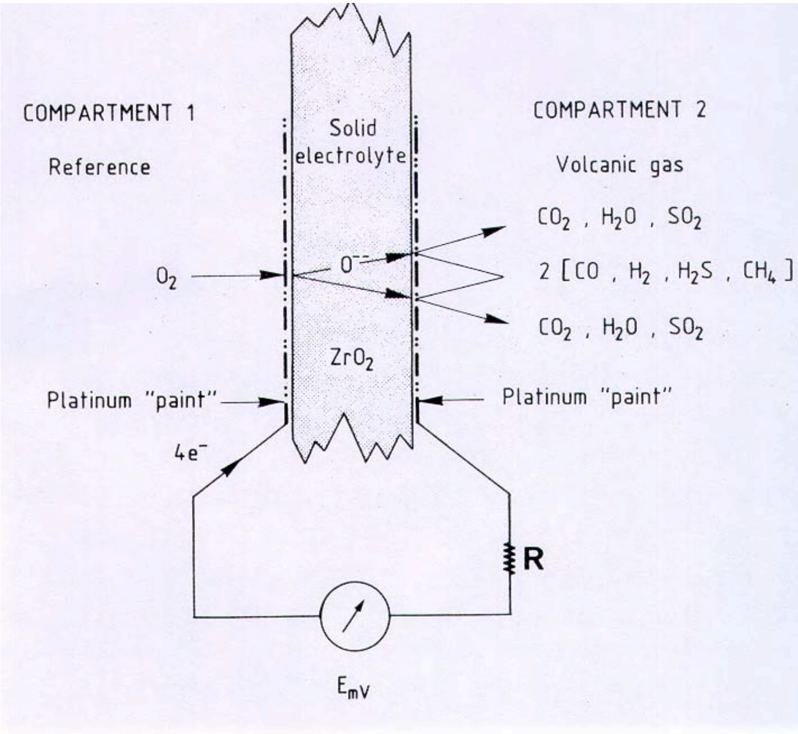
- MolSieve : noble gases, N_2, CO, ...

- Silica-PLOT : SO_2, COS, H_2S, ...

- Scientific objectives :
  - Noble gases (isotopic and elemental composition)
  - Stable isotopes (C, O, N)
  - Molecular composition

- Method :
  - Separation line (getter, membrane)
  - Ionization source (microtips)
  - Time-of-Flight Mass spectrometer

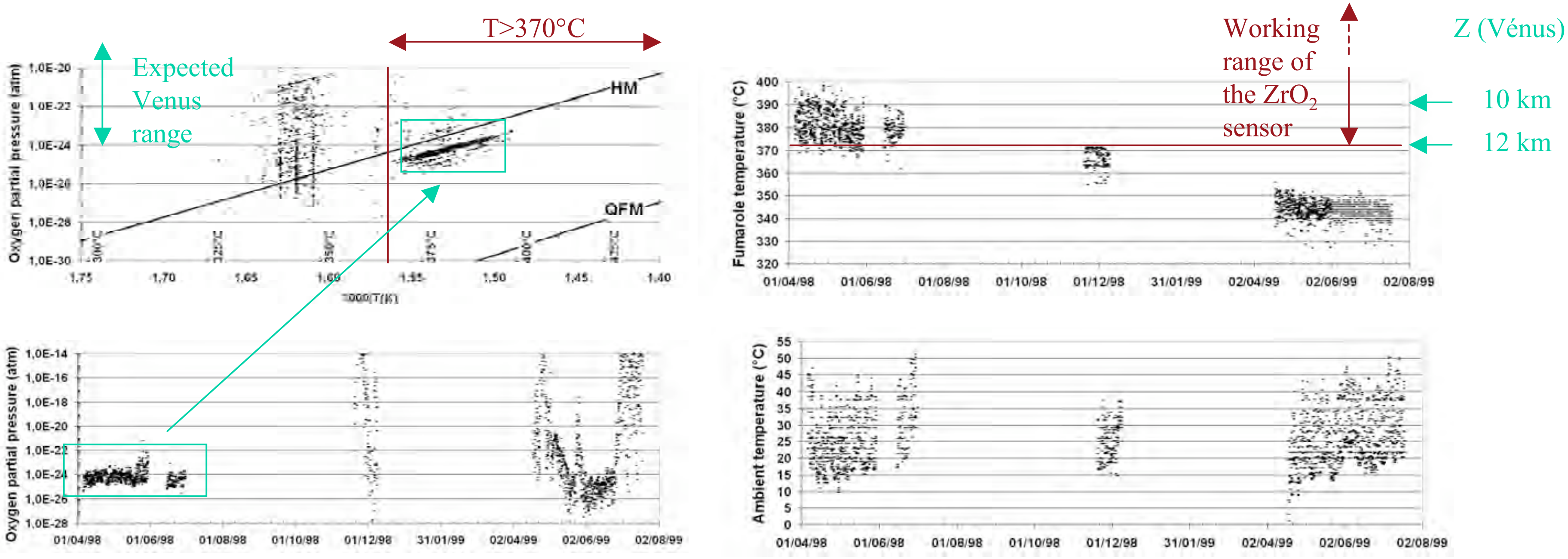
Electrochemical measurement of O_2 fugacity



Principle of zirconium sensor (ZrO_2)

- Scientific objectives :
  - Constrain thermochemical models of the deep atmosphere.
- Principle :
  - Fuel cell.
  - Combustion of atmospheric gases.
  - Measurement of a current, which is the counterpart of oxygen ions through the electrolyte.
- Advantages :
  - Very light sensor : a few grams
  - Directly works at high temperature.

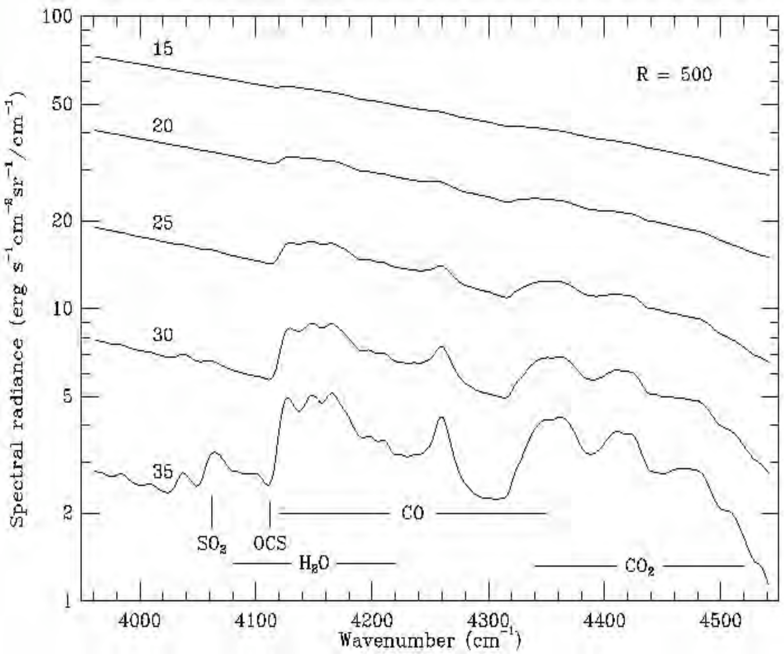
Example of O_2 measurement in a volcanic hot vent

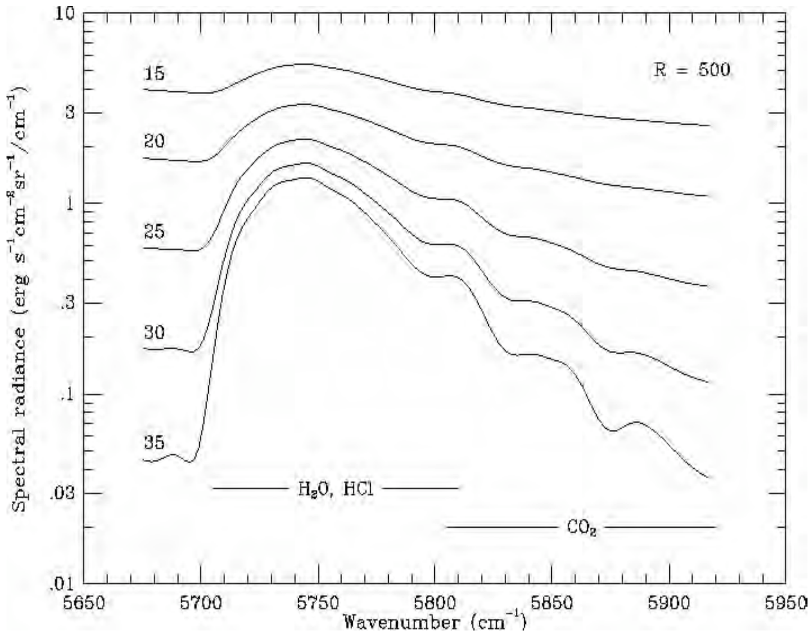


Continuous measurement of the oxygen fugacity in a hot vent of a volcano, Aeolian Islands, Italy. It is clearly seen that, above 370°C (643.2K), the oxygen sensor clips on the actual value of the fumarolic oxygen fugacity.

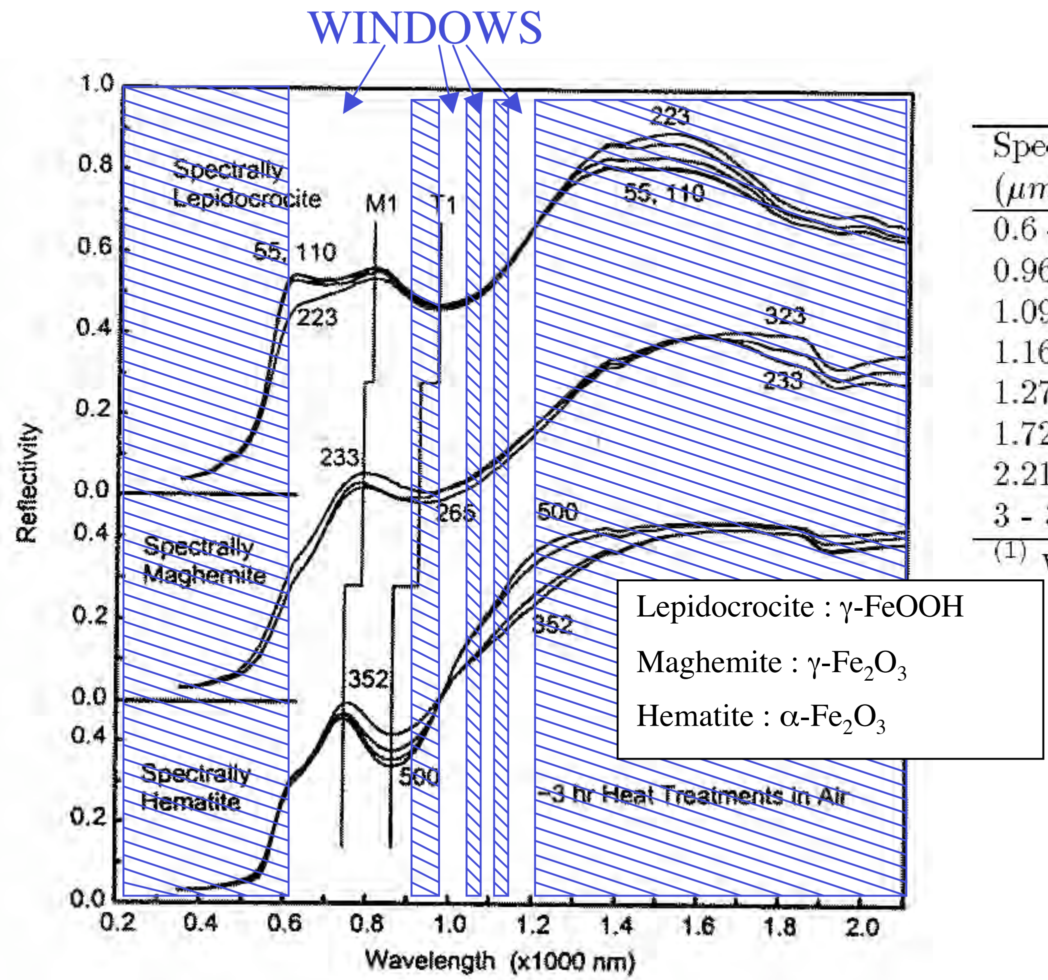
Thermal IR atmospheric spectra

- Simulation of atmospheric spectra seen from different altitudes by a spectrometer looking downwards, working at x 500 resolving power.





Spectral reflectivity of the surface



Transparency windows

Spectral interval (μm)	Transparency length [(1)] (τ=1)	Nature of the signal
0.6 - 0.9	1.5-10 km	Solar flux
0.96 - 1.035	15 km	Solar flux
1.09 - 1.11	20 km	Solar flux
1.16 - 1.195	10 km	Solar flux
1.27 - 1.28	1 km	Solar flux
1.72 - 1.75	1 km	Thermal emission
2.21 - 2.46	100 m	Thermal emission
3 - 3.7	100 m	Thermal emission

[(1)] without Rayleigh diffusion.

Note that, at all wavelengths between 0.5 and 1.20 μm, at least 1 or 2% of the solar light seems to reach the surface.